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Comparison of Planar and Spherical Near-Field Antenna Measurements for a 60 GHz Dual-Polarized Probe and 60 GHz Offset Reflector Antenna

Paula Irina Muntianu, Olav Breinbjerg
Department of Electrical Engineering
Technical University of Denmark
2800 Kongens Lyngby, Denmark
paipo@elektro.dtu.dk

Abstract—A comparison of 60 GHz planar and spherical near-field antenna measurements for two widely different antennas under test is presented to demonstrate how the non-ideal aspects of the measurement systems affect the far-field radiation patterns for mm-wave antennas. In general, a very good agreement is observed but clear differences are also noted.

Index Terms—antenna, near-field, mm-waves, measurement.

I. INTRODUCTION

Several challenges are encountered in near-field measurements of mm-wave antennas due to the small wavelength; non-ideal aspects of the measurement system which may be insignificant at longer wavelength may now become significant. These include mechanical alignments errors such as deviations from perfect plane or spherical scanning surfaces and non-orthogonality of rotation or translation axes, bending of cables and rotation of rotary joints, temperature variations, and increased path loss unless this is compensated by increased gain of the antenna under test or the range probe [1] [2].

In this paper we compare 60 GHz far-field radiation patterns from planar near-field (PNF) and spherical near-field (SNF) measurements to investigate how these non-ideal aspects affect the two different measurement systems. The PNF measurements are conducted at the DTU Planar Near-Field Antenna Measurement Facility which is a medium-accuracy system used for in-house research and teaching while the SNF measurements are conducted at the DTU-ESA Spherical Near-Field Antenna Test Facility which is an ESA external reference laboratory for high-accuracy testing of space-technology antennas. The main challenge for the PNF measurements is the mechanical alignment while for the SNF measurements it is the 83 dB path loss due to the 6 m measurement distance.

The comparison is done for two widely different antennas under test (AUT) developed at DTU. The first is a 60 GHz dual-polarized probe including an ortho-mode transducer (OMT) and switch [5] and the second is a 60 GHz metallic 3D-printed offset dual-reflector antenna with integrated conical feed and circular-to-rectangular transition [8]. The comparison includes co-and

cross-polar radiation patterns, on-axis directivity, and on-axis polarization parameters; for the dual-polarized probe it also includes the channel balance.

The paper is organized as follows: In Section II the PNF and SNF measurement facilities are described as are the parameters for the measurements of the two AUTs. In Section III the dual-polarized probe and the offset dual-reflector antenna are described. Section IV presents the comparison of the PNF and SNF measurements results for the dual-polarized probe, and Section V the comparison for the offset dual-reflector antenna. Finally, Section VI presents the conclusions.

II. DTU ANTENNA MEASUREMENT FACILITIES

A. Planar Near-Field Facility

The DTU PNF Antenna Measurement Facility, see Fig. 1 is based on a $0.8 \times 1.5 \text{ m}^2$ planar scanner with the scan plane planarity being estimated to be within a few tenths of mm, depending on the scan area. Two motor controllers and two step motors from JVL provide a xy -resolution of 0.0125 mm [1]. The PNF operational capability was extended to mm-wave range by integrating into the system an Agilent E8361A VNA operating up to 67 GHz, two cables from Pasternack working up to 65 GHz, a 40-60 GHz open-ended circular waveguide probe (OECW) based on a WR-19 OMT from Millitech but used in one polarization. To reduce the losses, the cables lengths were selected to be short 1 m and 1.5 m. The scan area was limited to $200 \times 220 \text{ mm}^2$ to reduce the cable bending and electrical characteristics variation. The data processing and control is implemented in a MATLAB program.

For PNF testing of the dual-polarized probe, full-scan measurements are carried out over a $200 \times 200 \text{ mm}^2$ scan area with a 2.4 mm sampling step in both horizontal and vertical directions. The duration of one scan is 8 hours for 83×83 scan points. The validity region is calculated to be $\pm 62^\circ$ for this area size, with a 40 mm probe-AUT distance and 52 mm diameter aperture of the dual-polarized probe.

For the metallic 3D-printed offset dual-reflector antenna full-scan measurements are conducted over a $300 \times 300 \text{ mm}^2$

scan area with 2.4 mm sampling step. The validity region is determined to be $\pm 76^\circ$ and the probe-AUT distance is 2.5 cm, selected as a compromise between reducing multiple reflections and maximizing the validity region. The OECW is manually rotated 90° to measure the AUT's orthogonal components. Thus, for the PNF measurements the OECW is probe for both the dual-polarized probe and the offset dual-reflector as AUTs.

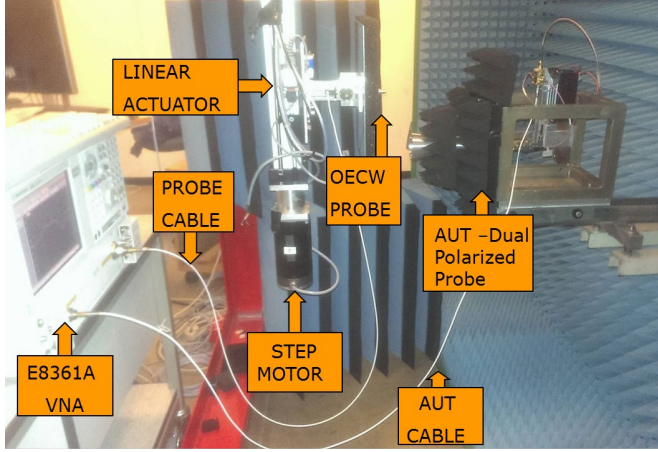


Fig. 1. DTU PNF Antenna Measurement Facility.

B. Spherical Near-Field Facility

The DTU-ESA Spherical Near-Field Antenna Test Facility is located at the Technical University of Denmark (DTU) and is operated in cooperation with European Space Agency (ESA). The instrumentation is shown in Fig. 2. The facility includes a spherical near-field scanner equipped with a RF system from MI Technologies. The RF system consists of a MI-1797 measurement receiver and a MI-3103 synthesized signal source. Two RF signals (signal and reference) are measured in amplitude and phase by the receiver and the AUT is rotated during measurement about θ - and φ -axes. The system is operated by a PC. For accurate measurement of the AUT angular position two Inductosyn encoders are used which allow to read the AUT position, within an accuracy of 0.001° in θ and φ . The mechanical alignment is performed by making use of a theodolite which is installed on the probe positioner. The instrumentation used at frequencies above 18 GHz includes a MI-3383 multiplier (4th harmonic), two MI-3346 mixers (4th harmonic), a LO extender, and a 20 dB coupler. At lower frequencies, the AUT is transmitting and the probe is receiving, while for frequencies above 18 GHz the direction of signal propagation is reversed. The reasons for this are: the cable going through the AUT positioner and the two rotary joints are operating only up to 18 GHz and installing the frequency multiplier above the rotary joints would require installing the coupler here and a second cable for reference channel to be installed in the AUT positioner which currently is not possible, see Fig. 2.

For SNF testing full-sphere measurements are conducted with a sampling step of 1° in θ and 3° in φ and approximately 3 hours duration of a measurement for the dual-polarized probe, and 1° in θ and 1.25° in φ with approximately 6 hours duration

of a full-sphere measurement for the offset dual-reflector antenna. Here a 25 dBi SGH is the probe with 90° manual rotation for measurement of two orthogonal components of AUT field. For SNF measurements, the SGH is probe for the dual-polarized probe, while the dual-polarized probe is probe for the offset dual-reflector antenna.

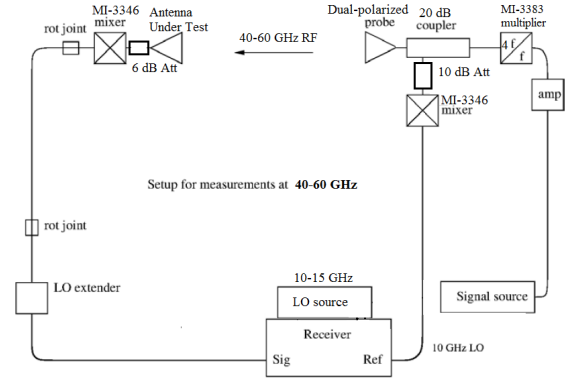


Fig. 2. Instrumentation Setup for 40-60 GHz SNF Antenna Measurement Facility.

III. ANTENNAS UNDER TEST

A 60 GHz dual-polarized probe and a metallic 3D-printed offset dual-reflector antenna are tested in SNF and PNF measurement facilities as antennas under test and the radiation pattern, directivity levels, on-axis axial ratio, and tilt angle results are compared.

A. Dual-Polarized Probe

The dual-polarized probe is a first-order ($\mu = \pm 1$) probe, a conical horn based on a SPDT (Single Pol Double Throw) switch from Ducommun up to 67 GHz, a WR-15 OMT from Sage Millimeter (50-75 GHz) both components with 40 dB isolation, a square to circular transition from Sage Millimeter (3.75 mm to 3.58 mm), cables and two coaxial-to-waveguide adapters up to 67 GHz for OMT-switch connection [3]. A 27 dBi directivity conical horn is designed by using WIPL-D software with 52 mm inner aperture diameter and 190 mm length and in-house manufactured, see Fig. 3.

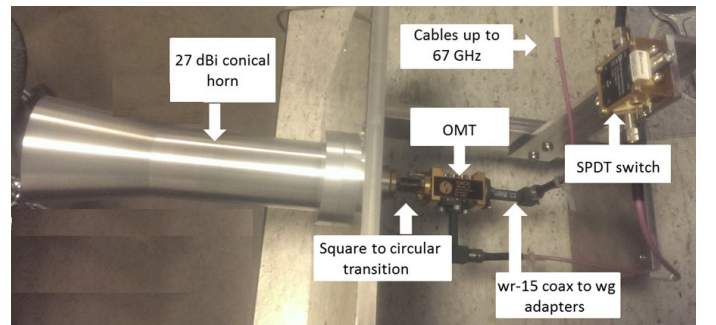


Fig. 3. 60 GHz Dual-Polarized Probe.

B. Offset Dual-Reflector Antenna

The metallic 3D-printed offset dual-reflector antenna works within 56 to 66 GHz. The diameter of the main reflector is 9 cm, the height of the structure is around 13 cm, the directivity is around 32 dB, and the feed is based on WR-15 waveguide [4], see Fig. 4.

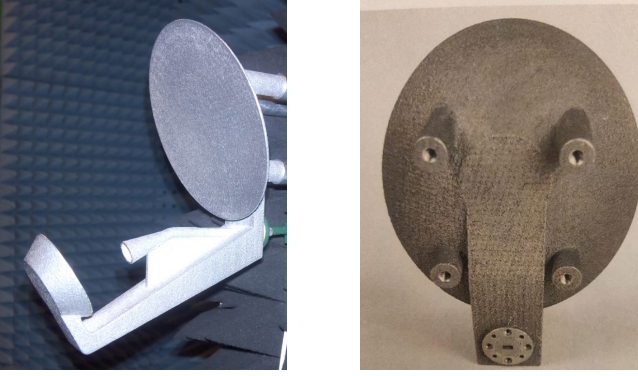


Fig. 4. Metallic 3D-printed Offset Dual-Reflector Antenna – side view (left) and back view with the waveguide feed (right).

IV. PNF AND SNF MEASUREMENT RESULTS FOR DUAL-POLARIZED PROBE

The 60 GHz dual-polarized probe is tested as an AUT in planar and spherical facilities for pattern calibration. All the results presented are at 60 GHz. The dual-polarized probe is tested without the switch by measuring the co- and cross-polar components for each port resulting in four measured signals - co and cross components at port 1 (p1) and port 2 (p2). Hence, four full-scan measurements (PNF) within 40-60 GHz range and four full-sphere measurements (SNF) over 56-62 GHz range are carried out for pattern calibration.

A. Radiation patterns

To validate our results the radiation pattern from SNF-measurements and PNF-measurements are compared with simulations, see Fig. 5 and Fig. 6.

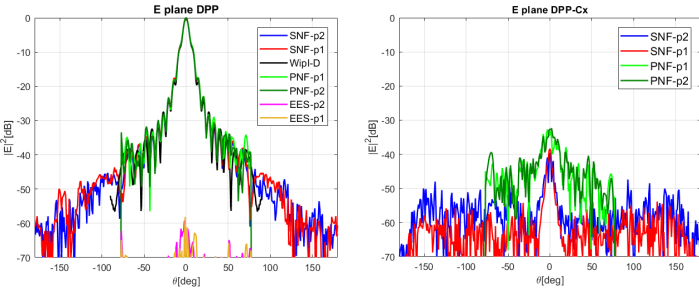


Fig. 5. Dual-polarized probe E-plane co-polar (left) and cross-polar (right) PNF and SNF measurements and simulations.

The co-polar SNF and PNF measurement results for E-plane and H-plane show a good agreement with simulations for both dual-polarized probe ports within the main beam region, with

some differences at lower pattern levels. The difference between PNF and SNF results is primarily caused by the truncated scan plane which means that the PNF results are unreliable outside of the region of validity; i.e. for $\theta > 62^\circ$, and completely absent for $\theta > 90^\circ$. The PNF result is also affected by stronger multiple reflections and stronger room scattering since the absorber lining is less. The difference between SNF and WIPL-D results may be due to the absence of the OMT and the probe absorber and support structure in the simulations.

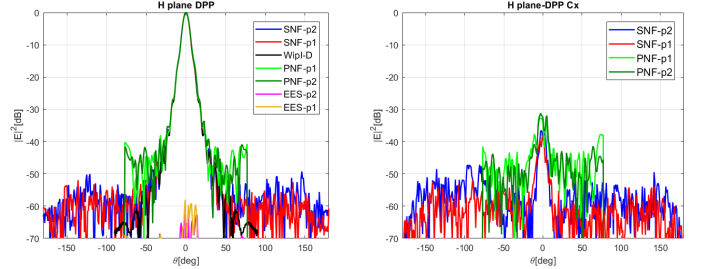


Fig. 6. H-plane co-polar (left) and cross-polar (right) PNF and SNF measurements and simulations.

The cross-polar components for E- and H-planes for SNF show a 4 dB lower on-axis level than the PNF results for p1, while for p2 the SNF data show around 7 dB lower on-axis level than PNF data. Simulated data do not exhibit cross-polar components for these planes. A possible explanation for the asymmetry of the PNF cross-polar pattern is the inaccuracy of the mechanical alignment. In SNF the mechanical alignment is more accurately performed by making use of the theodolite and alignment of the AUT positioner. In SNF the path loss is 83 dB for a 6 m distance at 60 GHz. Therefore, the SNF low levels of the co- and cross-polar components for E- and H-planes are likely to be affected by the high path loss.

Another aspect regarding the cross-polar component is the assumption of a perfectly linearly polarized probe. The SNF probe (SGH) is better linearly polarized than the PNF probe (OECW). Channel balance has an influence on cross-polar component. In SNF channel balance calibration has been conducted based on the three antenna measurement procedure [5], while in PNF a less complete calibration process has been carried out.

To quantify the differences the Equivalent Error Signal (EES) is calculated for the co-polar patterns for E-plane and H-plane and for the co-polar and cross-polar components for 45° and 135° planes for each of the ports p1 and p2; see Table 1 and Fig. 5 to Fig. 8. EES is calculated using [6]:

$$EES = 20 \log_{10} |10^{(S_{SNFdB}/20)} - 10^{(S_{PNFdB}/20)}| \quad (1)$$

The pattern standard uncertainty in dB (1σ) of the EES signal level is calculated for the main beam peak. The results from Table 1 demonstrate a very good agreement of the radiation patterns from SNF and PNF. For completeness the results for 45° and 135° planes from SNF and PNF are compared with simulations, see Fig. 7 and Fig. 8. For these planes both the co-polar and cross-polar components agree very well with simulations. Compared with E- and H-planes, here the cross-polar components show a better agreement with the

simulations. The reason is that for E-plane and H-plane the cross-polar has deep minimum with fast variation in φ but for $\varphi = 45^\circ$ and $\varphi = 135^\circ$ the cross-polar has a maximum with slow variation with φ .

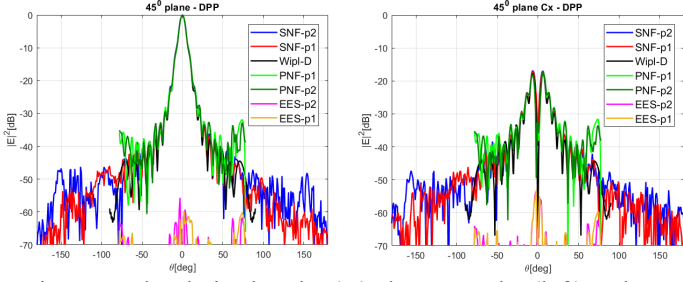


Fig. 7. Dual-polarized probe 45° plane co-polar (left) and cross-polar (right) PNF and SNF measurements and simulations.

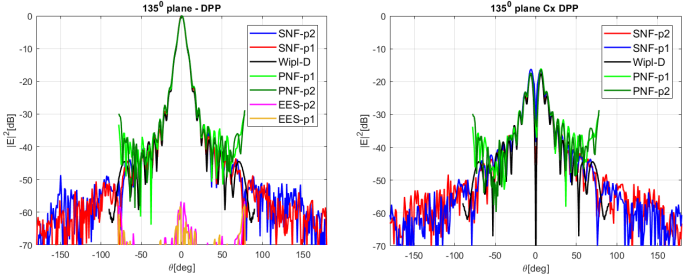


Fig. 8. Dual-polarized probe 135° plane co-polar (left) and cross-polar (right) PNF and SNF measurements and simulations.

Table 1: EES levels

Planes	E	H	45°		135°	
			Co	Cx	Co	Cx
Std. unc.(1 σ) [dB] p1	0.02	0.08	0.05	0.15	0.08	0.16
Std. unc.(1 σ) [dB] p2	0.02	0.06	0.1	0.14	0.1	0.02
EES mean [dB] p1	-85	-81	-83	-64	-84	-66
EES mean [dB] p2	-81	-84	-81	-63	-82	-65

B. Directivity levels, axial ratio and tilt angle

To further quantify the measurements results, the SNF and PNF directivity levels are compared with simulations. The top 7 dB of the directivity radiation pattern of the SNF and PNF measurement results are compared with each other and WIPL-D simulations are used as a reference, see Fig. 9. Axial ratio, tilt angle and peak directivity results for both measurement data sets are shown in Table 2.

It can be noted a very good agreement between measurements and simulations, with hundreds of dBs difference in the directivity levels between SNF data and simulations. The results from PNF indicate tenths of dBs lower directivity values compare to simulations and SNF measurements.

Comparing the axial ratio results from PNF and SNF it can be noted that the SNF data gives higher axial ratio values. The pertinent argument for this is the fact that the SNF probe (SGH) is better linearly polarized than the PNF probe (OECW).

Table 2: Measurement parameters PNF and SNF

Facility	PNF		SNF		WIPL-D
Ports	p1	p2	p1	p2	-
Peak directivity [dB]	27.1	27.1	27.3	27.3	27.4
Axial ratio [dB]	36.3	32.7	53.2	40.9	∞
Tilt angle [°]	0.7	89.3	89.3	-0.11	0

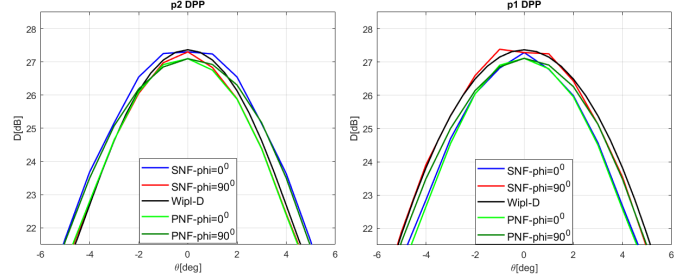


Fig. 9. Directivity: port 1 (left) and port 2 (right) measurements and WIPL-D simulations.

C. Channel balance

The reflection coefficient of p2 of the OMT is quite high showing values of around -6 dB at 60 GHz [3]. To compensate for the amplitude and phase differences between the two calibration signals at port p1 and port p2, channel balance is carried out in PNF and SNF facilities. In PNF two consecutive measurements of Axy factors are carried out for consistence in which the ratio of the probe signals at the probe ports is calculated. The AUT (dual-polarized probe) and OECW probe are horizontally polarized and the signal at p1 of the dual-polarized probe is measured, then the OECW is 90° rotated, the switch of dual-polarized probe is flipped and the signal at p2 is measured. The Axy measurements give 1.45 dB and -14° (Axy1) and 1.53 dB and -8° (Axy2). For SNF from three antenna measurement polarization calibration process [5] two Axy factors have been computed giving 0.02 dB and -0.15 dB for amplitude and 127° and 124° for phase. It can be noted that there is a small difference between the phase values of the two Axy factors while the amplitude indicates a 0.17 dB difference. These two different Axy values in SNF case reflect the measurement uncertainty. One possible explanation for differences in channel balance values between PNF and SNF is the channel balance calibration procedure. In SNF the calibration process is based on three antenna measurement involving two other antennas to determine the Axy factor. In PNF the calibration procedure is incomplete as the OECW probe is assumed to be perfectly linearly polarized. It should also be noted that the receiver systems for PNF and SNF included in the channel balance process are different. Another possible explanation for the differences in channel balance is the fact that in SNF during the calibration process the antennas are in the far-field from each other, which is not the case for PNF.

V. PNF AND SNF MEASUREMENTS RESULTS FOR OFFSET DUAL-REFLECTOR ANTENNA

The co-polar and cross-polar patterns at 60 GHz from the PNF and SNF facilities are compared with each other for E-plane and H-plane, see Fig. 10 and Fig. 11. The EES and the pattern standard uncertainty for the main beam peak (1σ) are computed for results quantification.

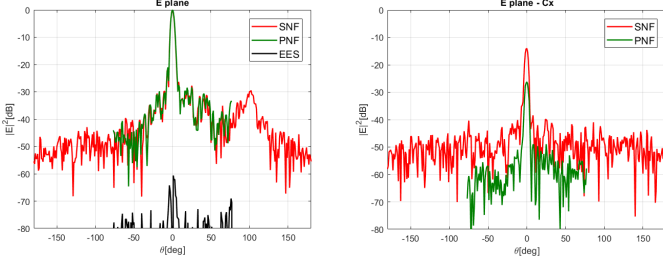


Fig. 10. E plane: co-polar (left) and cross-polar (right).

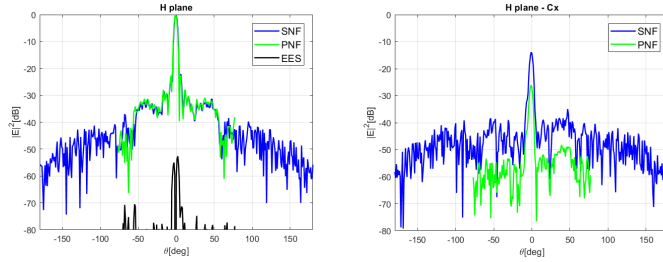


Fig. 11. H plane: co-polar (left) and cross-polar (right).

The SNF and PNF show a good agreement, the EES mean value indicating a level of -83 dB with a standard deviation of 11 dB for E-plane and a value of -87 dB and 12 dB for the mean and standard deviation for H-plane, respectively. The EES peak value of -60.2 dB generates a standard uncertainty of $1\sigma = 0.03$ dB for E-plane, while a peak value of -53 dB causes a standard uncertainty of $1\sigma = 0.3$ dB for the H-plane. The cross-polar results indicate around -26 dB and -14 dB on-axis levels for SNF and PNF, respectively. The high cross-polar in SNF might be caused by the lower dynamic range primarily due to larger measurement distance.

A. Directivity levels, axial ratio, tilt angle

The top 7 dB of the directivity results for E- and H-plane are compared for a more detailed investigation, see Fig. 12. The on-axis results for E- and H-planes indicate a value of 32.3 dB for SNF and 32.4 dB for PNF. It can be noted the displacement relative to the main axis of the PNF data for E-plane and H-plane, being more pronounced for H-plane and thus causing a ($\times 10$) larger standard uncertainty compared to E-plane. Some possible explanations for this are: inaccuracy of the mechanical alignment and uncertainties due to drift and flexing cables.

Axial ratio and tilt angle are computed for PNF and SNF giving 32 dB and 87.5° and 14 dB and 87.6° , respectively. The axial ratio result from PNF is larger than the SNF result corresponding to a lower PNF cross-polar component, while tilt

angle indicates almost the same value for both measurements results.

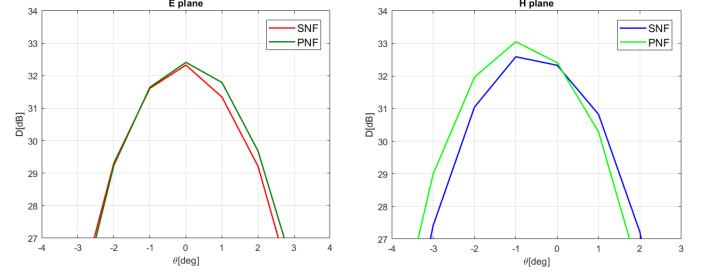


Fig. 12. Directivity results: E plane (left) and H plane (right).

VI. CONCLUSIONS

A 60 GHz dual-polarized probe and a 60 GHz offset dual-reflector antenna have been tested in PNF and SNF facilities and the measurement results have been compared in terms of radiation pattern, directivity levels, axial ratio, and tilt angle. The peak directivity results indicate a very good agreement between PNF and SNF measurements with only 0.2 dB and 0.1 dB differences in the values for dual-polarized probe and offset dual-reflector antenna, respectively. For the dual-polarized probe there is only about 0.07 dB peak directivity difference between SNF measurements and simulations. Radiation pattern measurement results for the two data sets show very good on-axis agreement within 0.02 dB for dual-polarized probe and within 0.03 dB for offset dual-reflector and an agreement with simulations down to -40 dB level. The differences between SNF and PNF results are likely to be caused by 83 dB path loss in SNF, while in PNF caused by inaccuracy of the mechanical alignment, room reflections due to less complete absorber lining, cable phase variation, lack of polarization calibration and inaccurate channel balance calibration. These are likely to affect the co-polar component and to dominate more the cross-polar component, axial ratio and tilt angle.

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